Targeting Resources Within Diverse, Heterogeneous and Dynamic Farming Systems: Towards a 'Uniquely African Green Revolution'

P. Tittonell, B. Vanlauwe, M. Misiko, and K.E. Giller

Abstract Smallholder farms in sub-Saharan Africa (SSA) are highly diverse and heterogeneous, often operating in complex socio-ecological environments. Much of the heterogeneity within the farming systems is caused by spatial soil variability, which results in its turn from the interaction between inherent soil/landscape variability and human agency through the history of management of different fields. Technologies and resources designed to improve crop productivity often generate weak responses in the poorest fields of smallholder farms. Thus, options for soil fertility improvement must be targeted strategically within heterogeneous farming systems to ensure their effectiveness and propensity to enhance the efficiency of resource (e.g. land, labour and nutrients) use at farm scale. Key issues in design of approaches for strategic targeting of resources include (1) inherent soil variability across agroecological gradients; (2) social diversity, farmers' production orientations and livelihood strategies; (3) farmer-induced gradients of soil fertility, their causes and consequences of efficient allocation of scarce resources; (4) competing objectives and trade-offs that farmers face between immediate production goals and long-term sustainability and (5) the complexity of farmers' own indicators of success. We used an analytical framework in which systems analysis is aided by survey, experiments and simulation modelling to analyse farming futures in the highlands of East Africa. Our work contributes to the development of 'best-fit' or tailor-made technologies, using combinations of mineral fertilizers and organic matter management from N_2-fixing legumes and animal manures. Thus, we hope to contribute to the design of a 'uniquely African green revolution' called for by UN Director General Kofi Annan, which fits technology interventions to the diverse and heterogeneous smallholder farming systems of sub-Saharan Africa.

Keywords Sub-Saharan Africa · Farm typology · Markets · Soil fertility · Resource use efficiency · Agricultural inputs

Introduction

Smallholder farms in sub-Saharan Africa are highly diverse and heterogeneous, often operating in complex socio-ecological environments. Much of the heterogeneity within the farming systems is caused by spatial soil variability, which results in its turn from the interaction between inherent soil/landscape variability and human agency through the history of management of different fields (e.g. Prudencio, 1993; Tittonell et al., 2005c). Classical 'green revolution' technologies designed to improve crop productivity often generate weak responses in the poorest fields of smallholder farms, as evidenced by, e.g., the large variability in fertilizer use efficiencies within single farms observed in East, West and Southern Africa (Vanlauwe et al., 2006; Wopereis et al., 2006; Zingore et al., 2007). Thus, options to restore productivity must be targeted strategically within heterogeneous farming systems to ensure their effectiveness and propensity to enhance

P. Tittonell (✉)
Plant Production Systems, Department of Plant Sciences, Wageningen University, 6700 AK Wageningen, The Netherlands; Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture (TSBF-CIAT), Nairobi, Kenya
e-mail: Pablo.Tittonell@wur.nl

A. Bationo et al. (eds.), *Innovations as Key to the Green Revolution in Africa*,
DOI 10.1007/978-90-481-2543-2_76, © Springer Science+Business Media B.V. 2011

the efficiency of resource (e.g. land, labour and nutrients) use at farm scale. Such options should be evaluated not only in terms of immediate benefits (which can be crucial in determining the adoption of a certain technology by farmers) but also by assessing their contribution to livelihood strategies and system sustainability in the long term (Giller et al., 2006).

Systems analysis aided by simulation modelling constitutes a means to evaluate options for sustainable intensification of farming systems, considering (1) their diversity, spatial heterogeneity and variability in time; (2) the scaling-up in space and time of the effect of single interventions operating at field plot scale, to infer consequences at farm and village scales in medium- to-long-term horizons (i.e. strategies) and (3) the possibility to perform scenario analysis with prospective or explorative purposes, evaluating the potential impact of factors that are external to the farm system, such as climate change or market developments. A first step in systems analysis and scenario evaluation consists in defining representative prototypes of fields, cropping sequences, farms or localities that must capture the key managerial, socio-economic and agroecological aspects of the systems under study. Their heterogeneity and diversity at different scales should be categorised, relying on solid understanding of the key drivers of such variability and using methodologies that allow comparisons across systems. Such cross-scale categorisation may also serve to define recommendation domains or socio-ecological niches (e.g. Ojiem et al., 2006) to which resources/technologies can be targeted.

The drivers of diversity, heterogeneity and farming systems dynamics can be grouped, in decreasing order of spatio-temporal scale, as site-specific conditions (agroecology, markets, population, ethnicity, etc.), soil–landscape associations, farm resource endowment, land use (crop types and livestock system), and long- and short-term management decisions (current soil fertility status and operational resource and labour allocation, respectively). Rather than static entities, farming systems are dynamic, subject to changing socio-economic and environmental contexts and risks (through, e.g., climatic or market variability). This chapter illustrates our conceptualisation of complex farming systems and presents examples of application of an integrative analytical approach (combining farm typologies, participatory research, experiments and modelling within the NUANCES analytical framework – www.africanuances.nl) to identifying intervention opportunities and pathways towards the sustainable intensification of smallholder systems in sub-Saharan Africa. The impact of the above factors and their implication for the promotion of green revolution technologies are examined using examples from mid- to high-potential agricultural areas of Kenya and Uganda (Table 1). Examples from a number of studies conducted in these sites and published elsewhere are used here for illustration.

The Biophysical and Socio-economic Environments

In targeting interventions to improve livelihoods through agricultural policy, investment in infrastructure or technology promotion, two main dimensions determining opportunities and constraints across locations are often considered: agroecological potential and market opportunities. To illustrate this, the six sites in Kenya and Uganda described in Table 1 are placed within a schematic plane defined by these two dimensions (Fig. 1a). Market opportunities are defined by the size, development and accessibility of major markets (e.g. proximity to urban and export markets, vial infrastructure, market information and transaction costs). For example, Meru South and Mbeere vary widely in agricultural potential but both districts are located close to the city of Nairobi (with an international airport) and are surrounded by the relatively highly populated areas and mid-sized towns of central Kenya, well connected through major national roads. Soils are inherently more fertile in Meru South and Mbale, located on the foot slopes of Mt. Kenya and Mt. Meru, respectively, and receiving ample rainfall. Soil organic C is a good proxy for the inherent soil fertility and agricultural potential of different sites in this case: soils with proportionally more clay under cooler and wetter climates tend to accumulate more organic matter due to larger primary productivity (more water and nutrient availability for plant growth) and slower rates of organic matter decomposition (lower temperatures and physicochemical protection of C within the soil matrix).

However, biophysical potential and market opportunities, which are also frequently correlated, are not

Table 1 Main characteristics of the case-study sites in three sub-regions of East Africa (from Tittonell et al., 2010)

	Central Kenya		Western Kenya		Eastern Uganda	
Characteristics	Meru South	Mbeere	Vihiga	Siaya	Mbale	Tororo
Biophysical						
Altitude (masl)	1,500	1,100	1,600	1,200	1,600	1,100
Rainfall (mm)[a]	1,600	700	1,800	1,400	1,200	1,100
Dominant soil types (FAO)	Nitosols, ferralsols	Lixisols, arenosols	Nitosols, ferralsols	Ferralsols, acrisols	Ferralsols, acrisols	Acrisols, vertisols
Landscape	Strongly undulating, slopes up to 45%	Fairly flat to gently undulating, slopes <5%	Gently undulating, slopes 5–20%	Fairly flat, slopes <3%	Gently undulating, slopes 5–10%	Fairly flat, slopes <3%
Socio-economic						
Population density (km^{-2})	800	400	1,000	350	350	250
Farm sizes (ha)	0.5–3	1–10	0.3–2	0.5–5	0.5–5	1–8
Production activities						
Major food crops	Maize, beans	Sorghum, cowpeas	Maize, beans	Maize, cassava	Bananas, beans	Cassava, sorghum
Major cash crops	Coffee, tea	Miraa, groundnuts	Tea, coffee	Sugar cane, cotton	Coffee	Cotton, tobacco
Livestock system	Zero grazing dairy systems and cultivation of fodder crops; improved cattle	Free-ranging local zebu and goats; night corralling	Tethered cattle grazing in compound and communal fields, and zero grazing	Free grazing and tethered local cattle, used for traction (ox-ploughing)	Zero grazing of cattle and goats; donkey used for transport	Free grazing in communal grasslands; local zebu

[a]In all sites, rainfall takes places in a bimodal pattern (i.e. long and short rainy seasons)

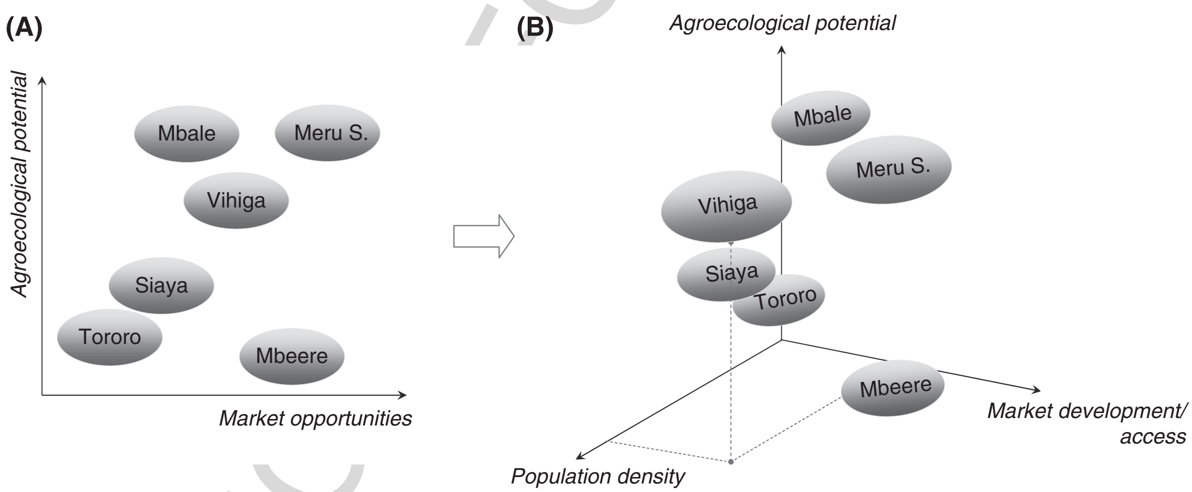

Fig. 1 Different sites in Kenya and Uganda ordered by their agricultural potential and market opportunities (**a**), and by these two factors plus population density (**b**). Details on the six sites are presented in Table 1. For guidance, the intersections with the market and population axes are indicated for Vihiga

enough to explain the observed diversity of livelihood strategies across and within locations. Historical, political and demographic processes in combination with local variability among households will ultimately determine the space of opportunities and constraints in which households develop. In Fig. 1b, the same

locations are now placed within a space defined by agroecology and markets plus a third dimension representing population density. Intuitively, one may expect higher population densities in areas with the highest agroecological potential and best market opportunities. That is not the case in this example, with more than 1,000 inhabitants km^{-2} in many areas of Vihiga district, due to ethno-cultural and historical backgrounds (Crowley and Carter, 2000). Population densities beyond a certain (site-specific) threshold are often inversely proportional to the availability of resources per household, but more people living in a certain area may also create more local market and/or job opportunities in rural communities.

Household Diversity and Livelihood Strategies

The diversity of livelihood strategies, which determine to a large extent production orientation and household objectives, has important implications for the targeting of agricultural technologies. Considering the two dimensions discussed above, natural resources and local markets, Dorward et al. (2001) distinguish three main livelihood strategies of the poor in rural areas, briefly (1) 'hanging in', which takes place in situations of poor natural resource potential and market opportunities, and where households engage in activities to maintain their current livelihood level (subsistence farming); (2) 'stepping up', in situations of high agricultural potential and where investments in assets are made to expand current production activities (semi-commercial farming) and (3) 'stepping out', when activities are engaged to accumulate assets that may eventually allow moving into different activities, not necessarily farming (i.e. migration to cities and/or local engagement in non-farm activities). At local scale, these strategies and their determinants are nuanced by differences between households in terms of resource endowment and social capital. In areas of high resource potential and ample market opportunities such as Meru South (cf. Table 1), different households may hang in, step up or step out, or pursue mixed strategies, such as investing in lucrative cash crops and re-investing their income into higher education for their children (to eventually step out). By contrast, areas of poorer natural and market potential will force most households to hang in.

Next to agroecology, markets and population density, rural–urban connectivity and off-farm opportunities contribute to shaping livelihood strategies. Access to non-farm income through remittances or employment in urban areas, or to off-farm income from selling labour locally in rural areas has been used in combination with indicators of production orientation and resource endowment to categorise household types in East Africa (Tittonell et al., 2005b). This constitutes a *functional* typology of households in which the position of the household in the farm developmental cycle is also considered (Fig. 2), expanding the more frequent approach of *structural* farm typologies used to categorise households (e.g. wealth rankings through indicators of resource endowment – Mettrix, 1993).

The various farm types thus defined engage in different income-generating activities, exhibit contrasting patterns of resource allocation and prioritisation of investments, and pursue different long-term livelihood strategies. For example, farms of type 1 and 5, relying largely on off-/non-farm income, have stepped out of agriculture as their main activity. In promoting technologies, farms of type 2 and 3 constitute the most promising target groups, since agricultural production represents their main source of income. In western Kenya, while type 2 includes wealthier households headed by respected aged farmers, type 3 includes mostly households headed by younger, enterprising farmers that show a high degree of participation in extension activities such as farmer field schools (Misiko, 2007).

Different sites across sub-Saharan Africa vary in their propensity to promote hanging-in, stepping-up or stepping-out livelihood strategies. Within a certain location, individual farms and decision makers differ in resource endowments, objectives, individual attitudes and ability to innovate. Although this variability must be recognised and categorised for better targeting of technologies, the socio-economic context should not be overlooked: most households in the study areas presented in Table 1 are below the poverty line, as indicated by the latest poverty mapping in the region (www.worldbank.org/research/povertymaps), and our categorisations basically distinguish between very poor, poor and less poor households. The ultimate beneficiaries of green revolution technologies in Africa – those that must be

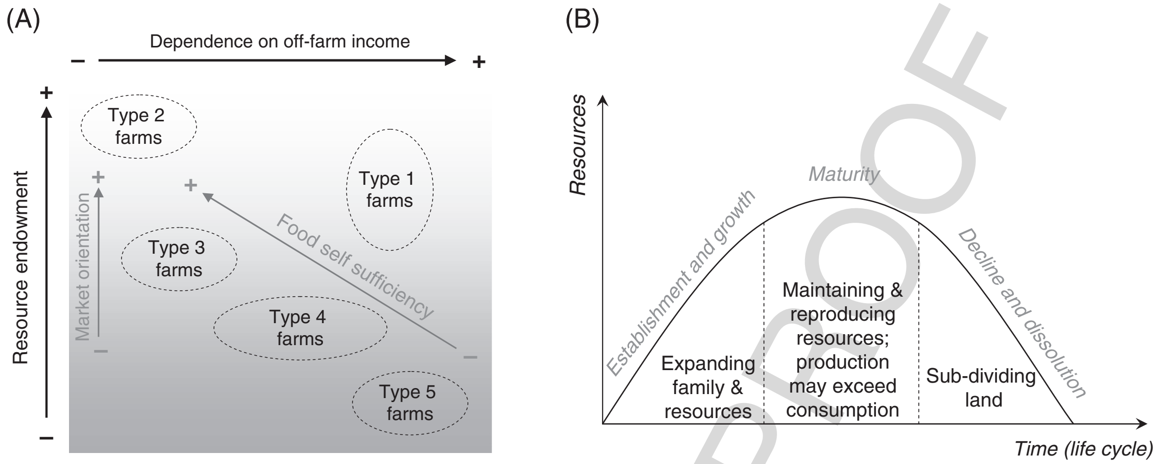

Fig. 2 (**a**) A typology of smallholder farms of East Africa, considering classical wealth indicators (resource endowment) plus source of income and production orientation to categorise households (adapted from Tittonell et al., 2010). (**b**) A schematic representation of the developmental cycle of farm households (Forbes, 1949) and its implications for resource allocation

targeted – are poor families, lacking cash and assets, and farming on small pieces of (frequently degraded) land.

Farm Heterogeneity and Resource Use Efficiency

Soil–landscape variability interacts with the regional and local factors discussed in the previous section to determine patterns of land use and resource allocation; such patterns lead in the long term to the creation of (human-induced) spatial heterogeneity within individual farms or soil fertility gradients. Resource use efficiency (units of output per unit of resource available) results from two components: resource capture (units of resource intercepted per unit of resource available) and resource conversion efficiency (units of output per unit of resource intercepted). Farm heterogeneity affects resource use efficiencies operating mostly on the efficiency of resource capture, leading to resource use efficiency gradients (Tittonell et al., 2007b) and to different patterns of responsiveness to technology interventions (e.g. non-responsive poor fields, responsive fields and non-responsive fertile fields – Tittonell et al., 2008). In cropping systems, poor resource use efficiencies may result from resource imbalances (Kho, 2000) or deficient agronomic management (Tittonell et al., 2007a).

Soil organic C was mentioned earlier as a good indicator of the agricultural potential of different sites, with greater contents in soils of finer texture (Fig. 3a). The fluctuation in average soil C levels for soils of similar texture (i.e. for a narrow range of clay+silt content) can be explained by climatic differences across sites, by local soil–landscape variability and, in particular, by management-induced farm heterogeneity. Farmers typically allocate more resources (labour, cash and nutrients) to fields that are perceived as more fertile or that are more convenient to manage (Fig. 3b), reinforcing this variability. In intensively cultivated farming systems, resource imbalances are also often closely associated with soil fertility gradients. For example, the pattern of variation in soil organic C and P availability illustrated in Fig. 3c can be commonly observed across farming systems; while soils with poor P availability may have relatively high or low soil C contents, high P availability is found only in soils with soil C contents above a certain threshold value. Such co-variability in C and P has been induced by farmers' management, with high concentrations of both C and P often found in gardens and fields closer to the homesteads. Another type of management-induced interaction is the use of improved cultivars in combination with nutrient inputs (Fig. 3d). In soils of similar organic C contents, farmers obtained larger yields when they planted hybrid maize compared with local varieties. Although improved cultivars may improve resource conversion efficiencies

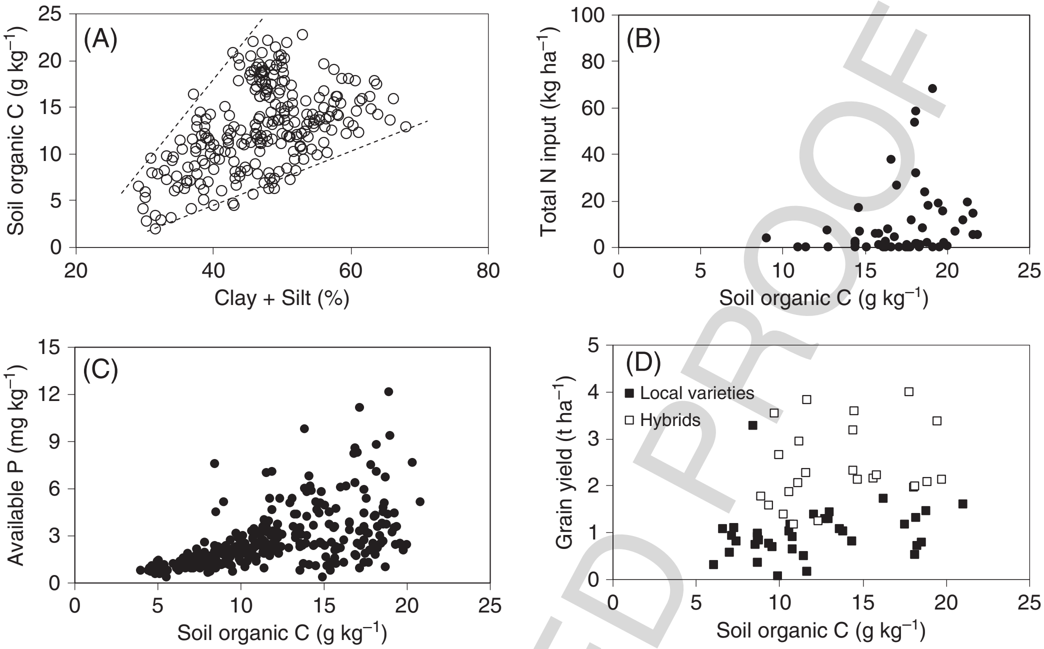

Fig. 3 (**a**) Weighted average soil C vs. average clay+silt contents at farm scale in 250 farms from Kenya and Uganda (Table 1). (**b**) N input as organic or inorganic fertilizers allocated to fields of different soil C contents in 15 farms of western Kenya. (**c**) Relationship between soil available (Olsen) P and soil organic C for 190 fields sampled in western Kenya. (**d**) Grain yield of local varieties and hybrids of maize vs. soil organic C content measured in 45 farms of western Kenya

(e.g. through larger harvest indexes), the yield differences in Fig. 3d were also partly due to the more frequent application of nutrient inputs to fields planted with hybrids.

Smallholder farmers are normally careful to allocate their limited production resources to the most profitable activities (in theory, to those that yield the highest marginal returns – Ellis, 1993). In systems where pressure on the land restricts the possibility of fallow or the availability of common grazing land, nutrient resources may enter the farming system chiefly via fertilizers and feedstuffs for livestock (if present). Let us consider the example of using animal manure in farms of western Kenya (Table 2). If all the manures potentially available for application to crops in these case-study farms were evenly spread over their total area, the average application rates would vary between ∼10–40 kg ha^{-1} for N and 1–6 kg ha^{-1} for P. As these rates are unlikely to induce substantial crop responses, farmers tend to concentrate on the available nutrient resources creating zones of soil fertility within their farms.

Cattle densities are low in most of SSA (e.g. between 1 and 5 heads km^{-2}, with values > 5 heads km^{-2} only in certain spots within the highlands of East Africa – cf. www.ilri.org/gis), and cropland-to-grassland ratios are ever increasing due to human population growth in high potential areas (www.earthtrends.wri.org). This reinforces the argument that the use of mineral fertilizers must be strengthened to sustain productivity of smallholder farms of sub-Saharan Africa. Given the wide diversity and heterogeneity of farming systems, however, the performance of fertilizers and their adoption may easily fluctuate from success to failure. Due to economic and environmental considerations, mineral fertilizers should be judiciously targeted to ensure high capture and utilisation efficiencies. Strategic targeting should consider not only the referred spatial heterogeneity but also the dynamics of the farming systems.

Long-Term System Dynamics and Interventions

The way in which green revolution technologies are (or have been, so far) promoted depends largely on

Table 2 Potential availability of manure and C, N and P for application to crops in farms from different wealth classes in western Kenya as derived from resource flow analysis (adapted from Tittonell, 2003)

Village[a]	Resource endowment	Land cropped (ha)	Livestock heads (TLUs)	Potential manure availability (t year^{-1})	Potential application rates (kg ha^{-1})[b] C	N	P
Ebusiloli	High	2.1	4.0	8.4	960	38	6.1
	Medium	1.1	2.2	3.6	785	31	5.0
	Poor	0.5	0.8	1.1	528	21	3.3
Among'ura	High	2.3	2.3	3.5	212	8	1.3
	Medium	2.2	2.0	2.9	218	9	1.4
	Poor	1.0	1.7	2.0	408	16	2.6

[a]Ebusiloli (Vihiga district) is located in a highly populated area (∼1,000 inhabitants km^{-2}), closer to urban centres with easier access to markets; intensive (zero grazing, Friesian) livestock production systems predominate. Among'ura (Teso district) area is less populated (200–300 inhabitants km^{-2}), land is available for fallow, markets are far and the local (zebu) livestock graze in communal land

[b]Calculated over the total area of cropped land, assuming optimum manure handling and an average dry matter content of 80%, C content of 30%, N content of 1.2% and P content of 0.19%

the way in which farming systems are conceptualised. Input-based intensification often rests on the assumption that input use efficiencies are independent of resource stocks or availability. To clarify this point, Fig. 4 presents two simplified models of resource utilisation. The term 'stock' is used generically to indicate the value of a state variable. In this simplest model, there is no formal distinction between stock and availability; a fraction of the inputs (I) added temporarily increases the stock (S), and output (O) is produced by transforming a fraction of the increased stock:

$$\text{Stock} = S_0 + \Delta\text{Stock} \times \text{Time} \qquad (1)$$

$$\Delta\text{Stock} = \text{Input} \times R_\text{i} - \text{Output} \qquad (2)$$

$$\text{Output} = (\text{Stock} + \text{Input} \times R_\text{i}) \times R_\text{o} \qquad (3)$$

The three parameters of the model (cf. Fig. 4a) are the initial stock (S_0), the fraction of input added that is retained to increase the stock (R_i) and the fraction of the stock removed in the output (R_o). Note that, generically, R_i and R_o may represent resource capture and resource conversion efficiencies, respectively. The simplest model A was initialised with $S_0 = 100$, $I = 10$, $R_\text{i} = 0.4$ and $R_\text{o} = 0.2$; that is, inputs were added at a rate of one-tenth of the original stock of 100, 40% of the input added was captured and 20% of the new stock (increased by input addition) was removed in the output. Equilibrium was reached at $S_\text{e} = 16$ (when, Input × R_i = Output = 4), after the model was run for 34 iterations (Fig. 5a – cf. 'constant rates').

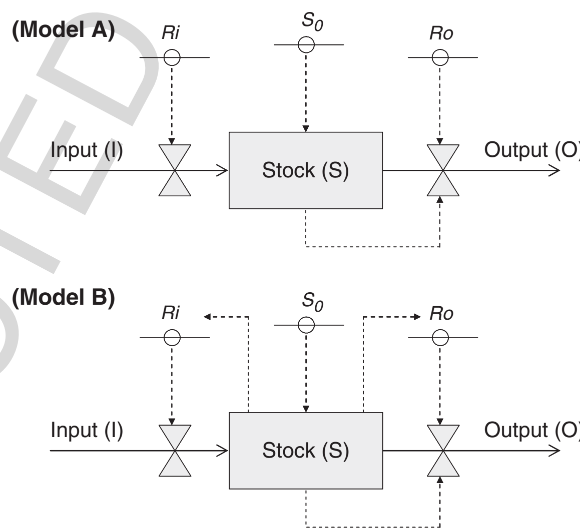

Fig. 4 Diagrams of two simplified models to illustrate resource use efficiency within farming systems. (**a**) The simplest case in which resource capture (R_i) and conversion (R_o) efficiencies are kept constant. (**b**) A case in which both R_i and R_o depend on resource availability (stock). See further explanation in the text

This simple model can be used to illustrate the effect of different types of interventions to restore productivity (Fig. 5b). Doubling the rate of inputs after equilibrium was reached will lead to doubling the value of S_e. Improving the efficiency of resource capture (R_i) by 50% will also increase S_e by 50%, often incurring less costs rather than doubling inputs (e.g. in cropping systems, R_i can be increased by planting on time, weeding frequently or using mulches). Improving the efficiency of resource conversion (R_o) by 50% will

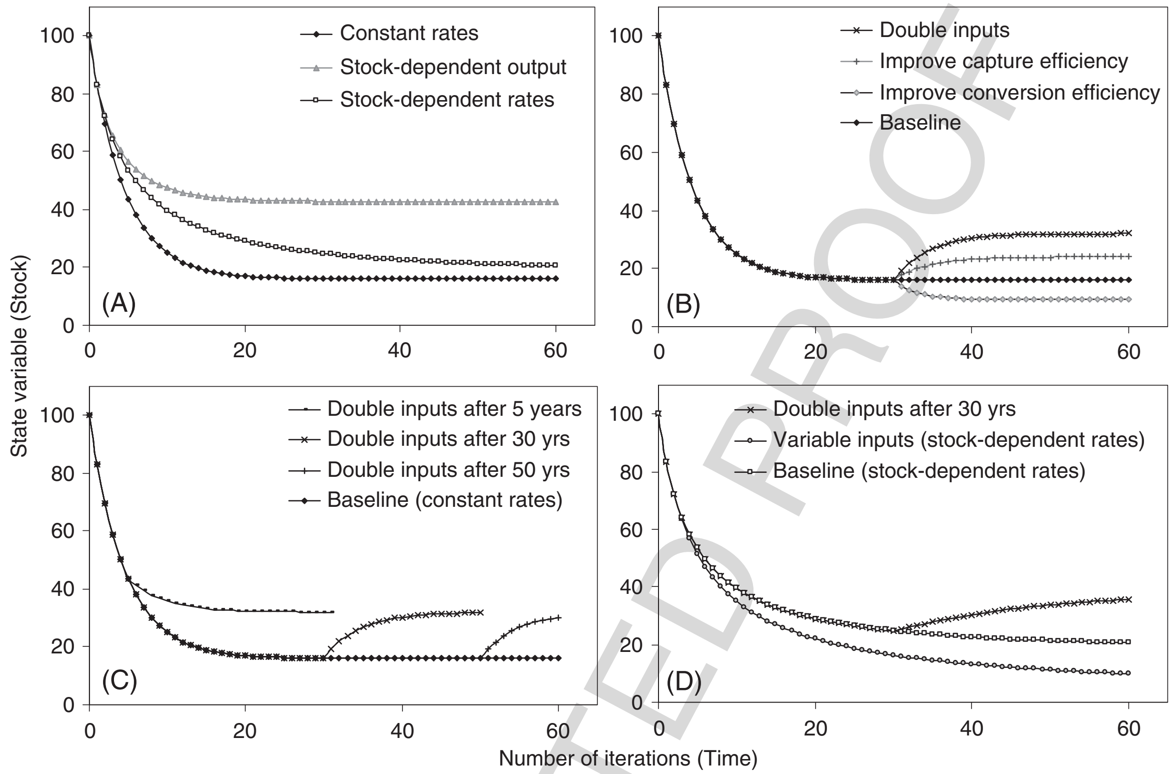

Fig. 5 Simulation of long-term system dynamics with models A and B depicted in Fig. 4. See explanation in text

reduce S_e by 50%. The latter is the case, in cropping systems, when farmers allocate less exigent crops in terms of soil fertility to fields that were cultivated for long periods without inputs; for instance, in western Kenya, maize growing is replaced with Napier grass in the outfields (Tittonell et al., 2005c), which has higher nutrient conversion efficiencies and further accelerates soil depletion.

A model slightly more complex is presented in Fig. 4b, in which both R_i and R_o are stock dependent, i.e. the efficiencies of resource capture and conversion decrease when the stock decreases. Within heterogeneous smallholder systems, resource capture efficiencies vary more broadly than the more conservative (e.g. crop type dependent) resource conversion efficiencies (Tittonell et al., 2008). In model B, R_i and R_o have been expressed simply as linear functions of S ($R_i = 0.004 \times S$ and $R_o = 0.002 \times S$). Due to such self-regulation mechanisms (or negative feedbacks), the rate of stock depletion is slower and equilibrium is reached only after 120 years at $S = 19$ (Fig. 5a – cf. 'stock-dependent rates'). This represents a more realistic case, as observed when, e.g., poorer crop yields are obtained in the poor outfields of a farm and therefore comparatively less nutrients are removed in the harvest. An intermediate case is that in which R_i remains constant and only R_o is stock dependent (Fig. 5a – cf. 'stock-dependent output'). Equilibrium is reached at higher values of S (= 43), and this can be the case when more than one resource is considered simultaneously. For example, the availability of a second resource that depends also on the stock S (e.g. water) affects the efficiency of conversion of the resource represented by S (e.g. a certain nutrient) (cf. Kho, 2000).

The underlying assumption behind 'blanket recommendations' in agriculture is often in correspondence with a resource utilisation model closer to model A, largely ignoring the long-term dynamics of farming systems. The different fields of an individual farm or a village have a history of use and management that places them in a certain position along the curve describing the trajectory of S (years under cultivation/fallow), or on a totally different trajectory of S

when the values of S_0, I, R_i or R_o would have been different. In model A, doubling the amount of inputs added will eventually double the value of S_e irrespective of the time at which the intervention takes place (Fig. 5c). However, field experimentation has demonstrated variable patterns of responsiveness to applied nutrients to fields with different history of use (e.g. Vanlauwe et al., 2006). By contrast, the initial response to doubling inputs will be slower in a self-regulatory system close to equilibrium, often discouraging farmers to continue applying inputs due to the poor initial response in productivity (Fig. 5d).

In reality, not only the stock but also the output rate participates in a feedback mechanism via farmers' decision making, i.e. fewer inputs are added as output rates decrease (a positive feedback). This will lead to even faster decline and lower values of S_e, in spite of the self-regulatory mechanisms (Fig. 5d – cf. 'variable inputs'). Most fields in intensively cultivated smallholder systems of SSA are in this situation and represent the target of green revolution technologies. When the system under study is the farm, the village or the region, this process is often termed 'downward spiral' or 'poverty trap' (e.g. Walker et al., 2006). The dynamics of a system cannot be understood without taking into account the dynamics and cross-scale influences of the processes above and below it. The context in which the system operates may be important in regulating the rate of inputs, through, e.g., market incentives (which may induce input use) or risks (which may deter input use), or when households are facing different stages of the farm developmental cycle (cf. Fig. 2). Finally, not only the rate of addition but also the timing, opportunity and quality of the inputs added play a role in shaping the dynamics of the system. For example, N inputs can be brought into the farm via mineral or organic fertilizers, feed concentrates for livestock or atmospheric N_2 fixation by legumes, inducing different efficiencies of N capture within the system.

Farmers' Objectives, Indicators and Trade-offs

Farmers' objectives and aspirations can be translated into quantifiable indicators by understanding the system attributes that concern the achievement of such objectives (López-Ridaura, 2005). For example, economic profitability and crop yields are two different indicators pertaining to the same attribute of a farming system, productivity. Nutrient balances are often used as indicators of system stability in the long term, although they do not really comply with all the desirable properties of a good indicator, among others, being easily measurable, having established thresholds and being easy to communicate to stakeholders. It is easily intelligible that negative nutrient balances may lead to nutrient depletion in the long term. However, nutrient balances are often most negative for the best yielding fields, and this is a puzzling concept to discuss with farmers (Tittonell et al., 2005a). Although farmers tend to concentrate resources in these fields (cf. Fig. 3b), the input rates are yet insufficient. Partial nutrient balances calculated in western Kenya indicate alarming rates of nutrient depletion, with removal in crop harvests often more than doubling nutrient inputs (Fig. 6a). The two encircled points in Fig. 6a represent two fields belonging to different farms; in spite of being cultivated with different rates of N inputs, the partial N balance was -22 kg N ha^{-1} in both cases. This highlights the need to analyse nutrient balances in relation to nutrient stocks, expressing the results in relative terms.

Even when major limiting nutrients such as N and P are applied to compensate crop removals, balances are negative for other nutrients that are not applied (e.g. K, S and Mg). At farm scale, maximising production often implies cultivating all the fields of a farm, even those of marginal fertility or with permanent impediments (e.g. steep slopes). This may lead to a trade-off between productivity and efficiency (e.g. nutrient capture efficiency), of which farmers are not always aware (Fig. 6b). Another typical example, and one that threatens the dissemination of conservation agriculture in SSA, is the trade-off between retaining crop residues in the field and using them to feed cattle, as fuel, sell them locally or add them to the compost. The best option would depend on the characteristics of the system and objectives, but the removal of crop residues from fields that received N or P fertilizers contributes to farmers' generalised perception that fertilizers 'spoil the soil' (Misiko, 2007).

The best indicator to analyse the system or the performance of a certain green revolution technology would also be different for different stakeholders. For formal comparisons across systems, indicators that are

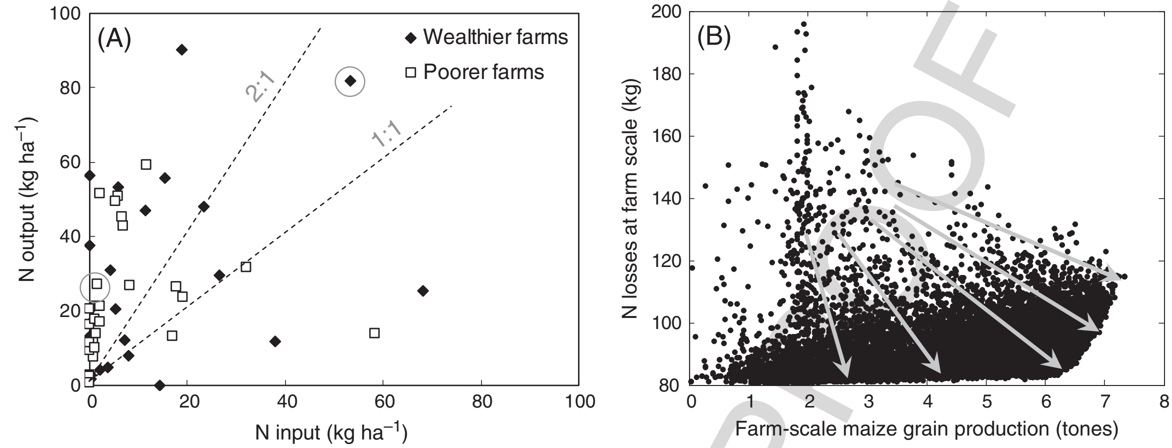

Fig. 6 (**a**) N outputs in crop harvests plotted against N inputs to the soil as organic and mineral fertilizers and crop residues in 15 farms of western Kenya. (**b**) Trade-off curve between maize productivity and N losses at farm scale obtained through optimisation using inverse modelling techniques (from Tittonell et al., 2007c)

often less obvious may yield important information. For instance, a system-level indicator of efficiency could be derived expressing soil fertility as kilogram of soil nutrients available per family member (e.g. for N, it could be calculated as *soil N content* × *soil depth* × *bulk density* × *area cropped/number of family members*). For instance, in Tororo (Table 1), soil P availability is often low (2–3 mg kg^{-1}) but average farm sizes are large (up to 8 ha). The kilograms of nutrients available per family member are a prerequisite to achieving food self-sufficiency; then, it is a question of how efficient is the production system (or what is the contribution of a certain technology) to capture and convert those nutrients into food.

'Green Evolution' – Promoting Inputs or Designing New Systems?

Promoting green revolution technologies under the same paradigm by which these technologies have been promoted in the past would most likely lead to new failure. A green revolution has to be 'uniquely African', as called for by Kofi Annan, due to the following particularities of smallholder systems in SSA:

1. Farms are heterogeneous and complex; variability within and between farms may yield promising green revolution technologies useless in terms of boosting productivity and long-term sustainability. Truly integrated soil fertility management must consider the various components of complex systems; for example, recommendations on the use of manure plus fertilizer must be based on realistic rates of application (in line with manure availabilities at farm scale), nutrient contents (often very poor in reality) and labour availability on the farm.
2. Smallholder farms are not necessarily commercially oriented; rural livelihood strategies are diverse, conditioned by agroecology and markets, and determined by household objectives, resource endowment and individual preferences of the decision maker. While some families 'make a living' out of agriculture, most keep the family land for a number of other reasons (e.g. social insurance) and regard agriculture as a secondary (or complementary) activity.
3. Land tenure and demographic processes are closely linked to culture and vary broadly across sites. The fact that in many cases, farmers do not have property rights on their land has led economists to argue that farmers (i) may lack motivation to invest in improving their soils and (ii) are not able to access credits to purchase agricultural inputs or reproduce their assets.
4. Most rural families in Africa are below the poverty line and farming already degraded land; assuming that promoting the use of agricultural inputs

through price policies or subsidies will automatically boost productivity and improve livelihoods is too simplistic. This is particularly the case when rural families have diverse sources of income and/or the (short or long term) aspiration to step out of agriculture.

Green revolution technologies should be targeted to diverse, heterogeneous and dynamic farming systems. Having one specific recommendation for each individual farm would be ideal, but impracticable, and thus it is necessary to categorise patterns of variability and identify possible entry points. Ideally, such patterns and opportunities should be easily recognisable by farmers, whose capacity for decision making should be built on solid knowledge about the systems they manage and their context. Far from simply promoting the use of agricultural inputs, a uniquely African 'green evolution' should contribute to the design of new systems, promoting improved resource use efficiencies, organisational skills and extension systems that involve farmers (shared knowledge and learning) and the development of rural markets. This calls for a truly interdisciplinary research and development effort, which must surpass the boundaries of agricultural disciplines.

References

Crowley EL, Carter SE (2000) Agrarian change and the changing relationships between toil and soil in Maragoli, western Kenya (1900–1994). Hum Ecol 28:383–414

Dorward AR, Anderson S, Clark S, Keane B, Moguel J (2001). Asset functions and livelihood strategies: a framework for pro-poor analysis, policy and practice. EAAE seminar on livelihoods and rural poverty, Wye, Kent, Imperial College, London

Ellis F (1993) Peasant economics. Farm households and agrarian development. Cambridge University Press, Cambridge, UK, 312pp

Forbes M (1949) Time and social structure. An Ashanti case study. In: Fortes M (ed) Social structure: studies presented to A.R. Radcliffe-Brown. Clarendon, Oxford, pp 54–84

Giller KE, Rowe E, de Ridder N, van Keulen H (2006) Resource use dynamics and interactions in the tropics: scaling up in space and time. Agric Syst 88:8–27

Kho RM (2000) On crop production and the balance of available resources. Agric Ecosyst Environ 81:223–223

López-Ridaura S (2005) Multi-scale sustainability evaluation. A framework for the derivation and quantification of indicators for natural resource management systems. PhD thesis, Wageningen University, Wageningen, 202pp

Misiko M, 2007. Fertile ground? Soil fertility management and the African smallholder. PhD thesis, Wageningen University, 208pp

Ojiem JO, de Ridder N, Vanlauwe B, Giller KE (2006) Socio-ecological niche: a conceptual framework for integration of legumes in smallholder farming systems. Int J Agric Sust 4:79–93

Prudencio CF (1993) Ring management of soils and crops in the West African semi-arid tropics: the case of the Mossi farming system in Burkina Faso. Agric Ecosyst Environ 47:237–264

Tittonell P, 2003. Soil fertility gradients in smallholder farms of western Kenya. Their origin, magnitude and importance. Quantitative approaches in systems analysis No. 25, Wageningen, The Netherlands, 233pp

Tittonell P, Misiko M, Ekise I, Vanlauwe B (2005a) Feeding-back the result of soil research: the origin, magnitude and importance of farmer-induced soil fertility gradients in smallholder farm systems. Emanyonyi Farmer Field School, Vihiga, western Kenya, July 27, August 17 of 2005. TSBF-CIAT, Nairobi, 23pp

Tittonell P, Muriuki AW, Shepherd KD, Mugendi D, Kaizzi KC, Okeyo J, Verchot L, Coe R, Vanlauwe B (2010) The diversity of rural livelihoods and their influence on soil fertility in agricultural systems of East Africa- a typology of smallholder farms. Agric Syst 103(2):83–97

Tittonell P, Shepherd KD, Vanlauwe B, Giller KE (2007a) Unravelling factors affecting crop productivity in smallholder agricultural systems of western Kenya using classification and regression tree analysis. Agric Ecosyst Environ 123:137–150

Tittonell P, Vanlauwe B, Corbeels M, Giller KE (2008) Yield gaps, nutrient use efficiencies and response to fertilizers by maize across heterogeneous smallholder farms of western Kenya. Plant Soil 313(1–2):19–37

Tittonell P, Vanlauwe B, Leffelaar P, Rowe E, Giller K (2005b) Exploring diversity in soil fertility management of smallholder farms of western Kenya I. Heterogeneity at region and farm scales. Agric Ecosyst Environ 110:149–165

Tittonell P, Vanlauwe B, Leffelaar PA, Shepherd KD, Giller KE (2005c) Exploring diversity in soil fertility management of smallholder farms in western Kenya. II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. Agric Ecosyst Environ 110:166–184

Tittonell P, Vanlauwe B, de Ridder N, Giller KE (2007b) Heterogeneity of crop productivity and resource use efficiency within smallholder Kenyan farms: soil fertility gradients or management intensity gradients? Agric Syst 94:376–390

Tittonell P, van Wijk MT, Rufino MC, Vrugt JA, Giller KE (2007c) Analysing trade-offs in resource and labour allocation by smallholder farmers using inverse modelling techniques: a case-study from Kakamega district, western Kenya. Agric Syst 95(1–3):76–95

Vanlauwe B, Tittonell P, Mukalama J (2006) Within-farm soil fertility gradients affect response of maize to fertilizer application in western Kenya. Nutr Cycling Agroecosyst 76:171–182

Walker B, Gunderson L, Kinzig A, Folke C, Carpenter S, Schultz L (2006) A handful of heuristics and some propositions for

understanding resilience in social–ecological systems. Ecol Soc 11(1):13. URL: www.ecologyandsociety.org
Wopereis MCS, Tamélokpo A, Ezui K, Gnakpénou D, Fofana B, Breman H (2006) Mineral fertilizer management of maize on farmer fields differing in organic inputs in the West African savanna. Field Crop Res 96:355–362
Zingore S, Murwira HK, Delve RJ, Giller KE (2007) Soil type, historical management and current resource allocation: three dimensions regulating variability of maize yields and nutrient use efficiencies on African smallholder farms. Field Crop Res 101:296–305